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Microstructural changes and mechanical properties of friction stir processed extruded AZ31B alloy

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Abstract

Friction stir processing has emerged as an effective method for improving the material properties locally through significant refinement and homogenization. Friction stir processing is a solid state process where the material beneath the shoulder and around the pin region undergoes severe plastic deformation resulting in dynamically recrystallised equiaxed grain structure. The extruded AZ31B magnesium alloy used in this work reveals limited ductility because of hexagonal closed packed structure and severe mechanical twinning. This article reports the effects of Friction stir processing parameters such as tool rotational speed (1000 rpm, 1200 rpm), tool traversing speed (40 mm/min, 75 mm/min and 105 mm/min) and shoulder diameter (18 mm and 24 mm) on microstructure and tensile properties of friction stir processed extruded AZ31B alloy. It is observed that the friction stir processing of the magnesium alloy with the tool shoulder diameter of 24 mm exhibited defect free processed zone when compared to the tool shoulder diameter of 18 mm for most of the tool rotational and traversing speeds. On processing, the work material is observed to have improved ductility and also an ultrafine equiaxed grain in the processed zone. The observations have been clearly explained in detail with the microstructures of the parent and processed zone.

keywords : Friction stir processing: Tool rotational speed, Tool traversing speed, Equiaxed grain;

1. Introduction

Magnesium is the lightest of all the engineering metals. It has a density of 1.74 g/cm^3, 35% lighter than aluminium (density of 2.7 g/cm^3) and more than four times lighter than steel (density of 7.86 g/cm^3) [1].

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The demand for magnesium alloy sheets as a light structural material and for functional parts in ground vehicles, aircraft and electronic industries has increased in recent years due to the lowest density among practically used metals, high specific strength and excellent damping capacity. However, magnesium is a hexagonal closed packed metal and has limited formability accompanied by brittle like behaviour at room temperature. Therefore, the formed products of wrought magnesium alloys are not yet economically reliable or feasible [2-5]. Recent results however indicated that at elevated temperatures it is possible to form AZ31 sheets under certain conditions, and even achieve superplastic like behaviour. The results also suggests that increase in ductility and formability can be achieved by refining and homogenizing the grain structure of the sheet [6,7]. Friction stir processing, a new solid state technique is based on Friction Stir Welding (FSW) which was invented by The Welding Institute (TWI) in 1991. One of the main advantages of the FSW is the grain refinement besides joining the material. FSP is a solid state process in which a specially designed rotating cylindrical tool, consisting of pin and shoulder is inserted into the plate / sheet. The rotating cylindrical tool is then traversed in the desired direction for property enhancement at a localized region. The material beneath the tool shoulder gets soften due to the heat produced by the rubbing action of the shoulder on the surface of the material. The heat produced will be lesser than the melting point of the material. The pin below the shoulder, which is inserted into the workpiece, causes mechanical stirring, due to which the material within the processed zone undergoes intense plastic deformation yielding a dynamically recrystallised fine grain structure [8-12]. FSP has the potential to become an effective method for microstructural modification or grain refinement in sheet metals.

Though large number of investigations has been carried out on friction stir processing of aluminum alloys, the study on friction stir processing of magnesium alloys is limited. Many researchers successfully used friction stir welding to join magnesium sheets. Selection of proper tool pin profile, tool shoulder diameter and tool material to friction stir weld AZ31B magnesium alloy were investigated by Padmanabhan et al. [13]. They found that the joints fabricated by high carbon steel tool with threaded pin profile and shoulder diameter of 18 mm exhibited superior tensile properties compared to their counterparts. Cavaliere [14,15] et al studied the room temperature and hot tensile properties of friction stir processed AM60B and AZ91 magnesium alloy sheets produced by high pressure die cast. They suggested that friction stir processed material possessed good strength and ductility values at room temperature because of very fine structure obtained by processing. Darras et al [12] examined the possibility of using FSP to modify the microstructure and properties of commercial AZ31B-H24 magnesium alloy sheets. Sato et.al investigated the effects of FSP on the microstructure of AZ91 alloy [16] .They investigated that FSP leads to finer and more homogenized grain structure. All the above literature are related to friction stir processing of magnesium alloys in which very less information was available related to the effect of friction stir processing on tensile properties of the base metal and friction stir processed metal. Hence the present investigation was carried out to study the effect of friction stir process parameters i.e tool traversing speed, tool rotational speed and tool shoulder diameter on tensile behavior, microstructure and to determine the process parameters that yield defect free friction stir processed zone.

2. Experimental set-up

The base material used in this investigation is extruded AZ31B grade magnesium alloy. The chemical composition obtained by Emission Vacuum spectrometer and mechanical properties of the extruded AZ31B alloy is shown in the Table 1 and 2 respectively. The extruded AZ31B alloy was received in the form of rectangular plate of dimensions 300 x 150 x 6 mm from Morgo Magnesium suppliers, Netherlands. The plates were then cut to the required size of 100 x 75 mm in a hacksaw machine. Friction stir processing on the wrought magnesium alloy was done along the longitudinal direction in an indigenously designed and developed friction stir welding machine with the following specification, a spindle motor capacity of 15 hp, maximum tool rotational speed of 2500 rpm, maximum translational speed of 135 mm/min and maximum axial load of 25 kN. The geometry of the hardened high carbon high chromium (HcHCr) steel (RC64) tool used for the study is shown in Fig. 1. The two friction stir tool composed of a pin with a diameter of 6mm, pin length of 5.8 mm and shoulder diameter of 18 mm [17] and 24 mm respectively. Friction stir processing was done with two shoulder diameter tools at three different traverse speeds such as 40 mm/min, 75 mm/min and 105 mm/ min under two tool rotational speeds of 1000 and 1200 rpm respectively.

All the experiments are carried out by single pass friction stir processing technique. The processed material is then subjected to metallographic examinations for visualising the defects such as tunnel and void in the processed zone and the tensile test is carried out to examine the mechanical properties of the processed material. The specimens for tensile test are sliced in the direction parallel to the direction of processing, as shown in Fig. 2. and then machined to the required dimension according to ASTM E2448 standard for sheet type material with a gauge length of 25 mm and a gauge width of 6 mm. Fig. 3 illustrates the dimensions of the tensile specimen. Tensile test is carried out in a computer interfaced universal testing machine of capacity 50 kN and the parameters such as yield strength, ultimate tensile strength, percentage of elongation are noted. The specimens for the metallographic examination were sliced to the required size and then polished with different grades of emery papers. Microstructure analysis was carried out at different regions of the processed zone with the help of an Optical microscope. Macrostructural analysis is also done on a processed zone to identify the presence of defects, location of defects and type of defect in the nugget region with the magnification of 20X.

Table 1 Chemical composition (wt %) of AZ31B magnesium alloy

Al	Mn	Zn	Cu	Mg
2.88	0.37	0.87	0.002	Balance

Table 2 Mechanical properties of AZ31B magnesium alloy

Yield strength (N/mm^2)	Ultimate tensile strength (N/mm^2)	Elongation (%)	Vickers Microhardness at 0.05 kg load (Hv)
212	267	8	77

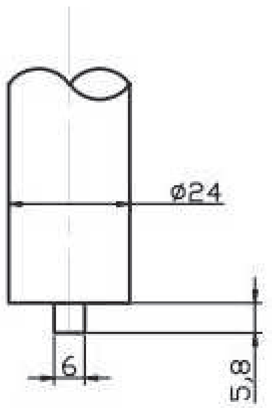


Fig. 1. Plain cylindrical tool

(All dimensions are in millimeter)

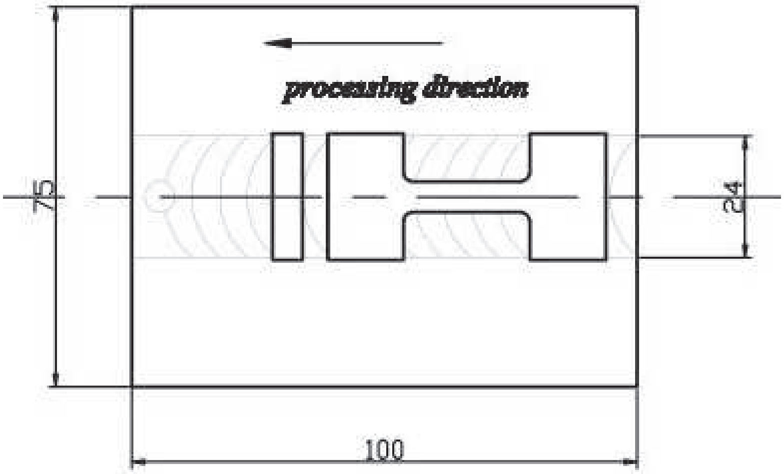


Fig. 2. Extraction of tensile specimen

(All dimensions are in millimeter)

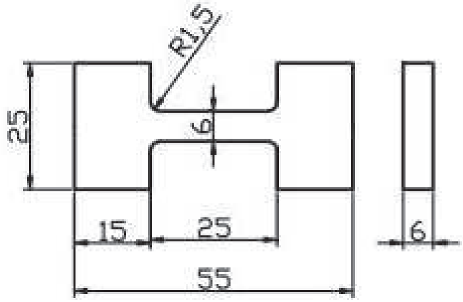
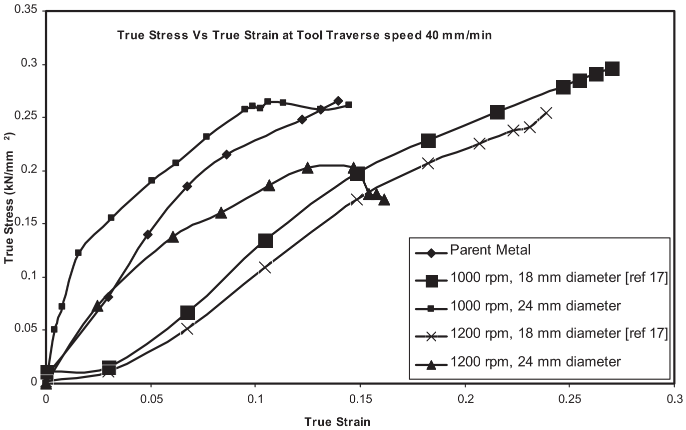


Fig. 3. Tensile specimen dimension (ASTM 2448)
(All dimensions are in millimeter)

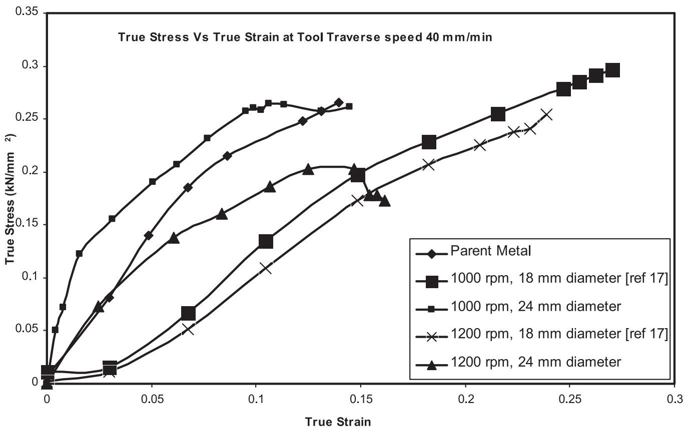
3. Results and discussion

3.1 Tensile properties

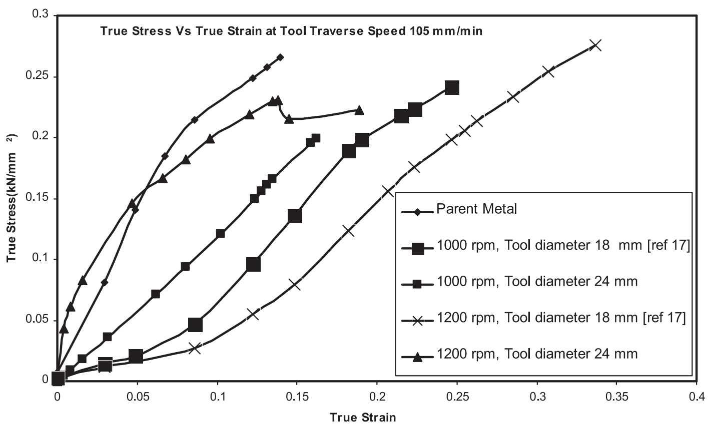
The significant improvement in mechanical properties of friction stirred processed material such as yield strength, ultimate tensile strength, percentage of elongation were evaluated. For each experimental condition, two specimens are tested and the average of the results is taken for analysis. The true stress strain curve for base material and friction stir processed material are constructed and shown in Fig. 4 (a-c). It is inferred that with the increase in tool rotational speed for a specific tool traverse speed enhanced the ductility for both the tool shoulder diameters due to the dynamic recrystallisation at higher temperature and presence of equiaxed grain structure in the processed zone. [18]. The increase in temperature at higher tool rotational speeds causes an increased frictional heating at the interface between the tool shoulder and the workpiece thereby causing a finer grainer refinements and enhancement in the percentage elongation, which is a measure of ductility. At higher tool traverse speeds, lower tool rotational speeds and less tool shoulder diameter, lower heat input conditions are observed causing a



a. True stress strain curve at tool traverse speed 40 mm/min



b. True stress strain curve at tool traverse speed 75 mm/min



c. True stress strain curve at tool traverse speed 105 mm/min

Fig. 4 (a-c). True stress diagram for tool traverse speed 40 mm/min, 75 mm/min, 105 mm/min reduced refinement of the grains in the processed zone. Moreover, it is also shown that the stress required to cause plastic deformation i.e. the flow stress of the friction stir processed region, where the grain size is three times smaller than that of the base material is lower than that of the base material and also the friction stirred zones show enhanced total strain of ductility. The increase in the percentage elongation of the friction stir processed region ranges from 1.25 to 1.82 times than that of the base material. This result confirms with the previous work reporting an enhancement in total strain with significantly lower strength during surface friction stirred zones [19]. Hence, the friction stir processed magnesium alloy might exhibit an increase in formability with the substantial reduction in applied load.

3.2 Macrostructure

Previous work on the friction stir processing of Aluminum alloys [10, 20] has reported that FSP is a viable tool for eliminating casting defects, porosity and modifying the microstructure. However, friction stir processing are subjected to other defects like excessive flash on the surface, pin hole, tunnel defect, piping defect, surface cracks etc [11,20]. Elangovan and Balasubramanian [20], Kim et al [21], Cao et al [22] have mentioned that the above mentioned defects occur in friction stir welding due to insufficient heat input, excess heat input, excessive turbulence of the plasticized metal and inadequate material flow and mixing. The above mentioned probable causes mainly depend upon the combination of tool traversing speed and tool rotational speed. In this study, tunnel defects, pin hole defects, surface defects such as excess flash and surface crack occurred during FSP. Hence, all the processed specimens were analyzed using optical microscope at a low magnification of 10X to study the quality of processed zone and they are presented in Table 3**.** It is observed that, a tunnel type of defects are present in the stirred region for most of the processed parameters with 18 mm tool shoulder diameter. This might due the lack of heat being generated at the pin workpiece interface and also at the tool shoulder and workpiece interface. With the tool shoulder diameter of 24 mm, surface flash and pin hole type of defect were observed only when the tool traverse speed was 40 mm/min. The defect free processed zone was observed when the tool traversing speed was increased. Hence, for the defect free processed zone and also for the increase in ductility, the minimum tool shoulder diameter, tool traversing speed and tool rotational speed should be 24 mm 75 mm/min and 1000 rpm respectively.

3.3 Microstructure

Fig.5 shows the optical micrographs of the extruded base metal as received, whereas Table 4 shows the optical micrographs of the nugget zone of friction stir processed material at various processing conditions. From the micrographs it is observed that the heterogeneity in the grain structure occurred in the base metal and it might be due to sudden reduction in the size of the plate from the billet during extrusion and also due to partial annealing. These elongated grains in the base metal are transformed into significant grain refinement in the nugget region of the friction stirred processed material. It has been reported that because of dynamic recrystallization due to the frictional heat between the shoulder and the workpiece, initial elongated grain structure are transformed into fine equiaxed grains [23].

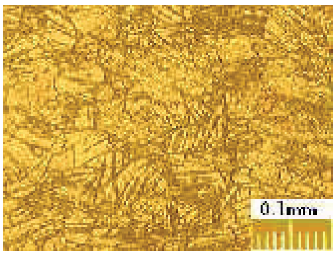


Fig. 5. Optical Micrograph of as received parent material (Magnification 200X)

Table 3. Macrostructure of Friction Stirred Processed material (Magnification 20X)

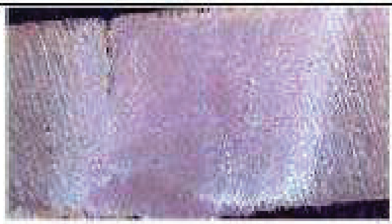
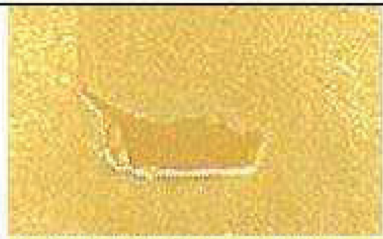
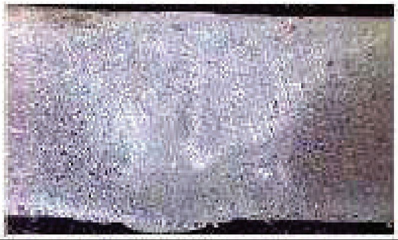
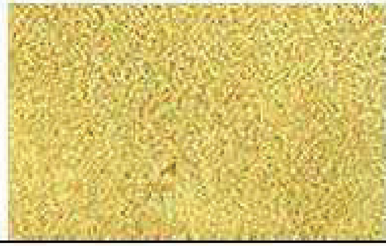
Tool Traverse speed mm/min	Tool Rotational speed rpm	Tool Shoulder Diameter =24 mm	Tool shoulder diameter= 18 mm	Defects / Probable causes	
		24 mm	18 mm	Shoulder Diameter 24 mm	Shoulder diameter 18 mm
40	1000			Defect on the surface of the plate Excess Heat input per unit length of the processed zone	Tunnel defect at the mid portion of the processed zone towards the advancing side
	1200			Pin hole defect beneath the pin Insufficient heat generation	Insufficient heat input and improper plasticization of the material in the processed zone
75	1000			No defect	Porosity A small defect near by the advancing side due to insufficient heat input to the base of the plate

Table 3. Cntd

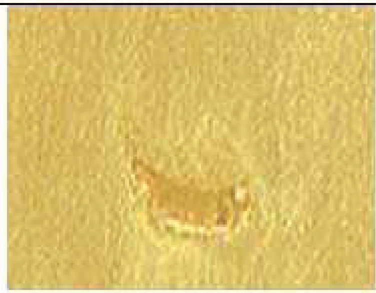
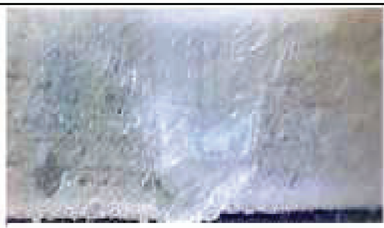
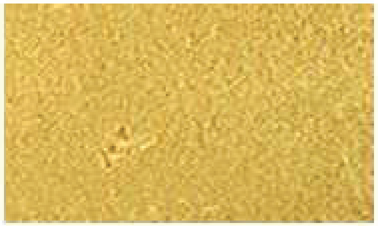
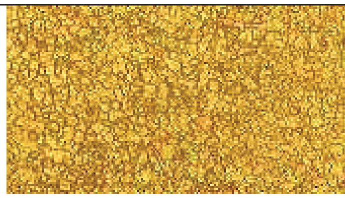
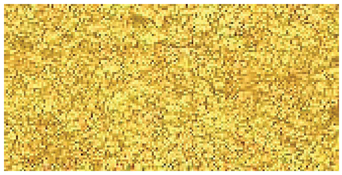
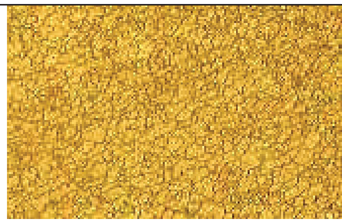
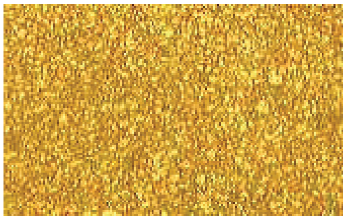
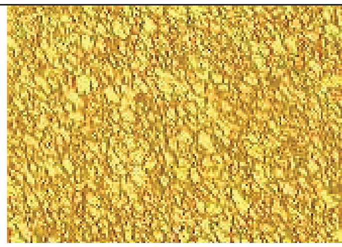
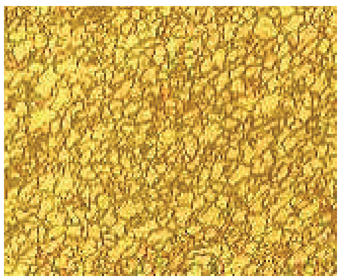
Tool Traverse speed mm/min	Tool Rotational speed rpm	Tool Shoulder Diameter =24 mm	Tool shoulder diameter= 18 mm	Defects / Probable causes	
		24 mm	18 mm	Shoulder Diameter 24 mm	Shoulder diameter 18 mm
75	1200			No defect	Tunnel defect at the mid portion of the processed zone towards the advancing side Insufficient heat input and improper plasticization of the material in the processed zone
105	1000			No defect	Tunnel defect
	1200			No defect	Pin hole defect towards the advancing side Insufficient heat input from the shoulder to the base plate

Table 4. Optical Micrographs (Magnification 200X) of friction stir processed material at the nugget zone

Tool Traverse speed mm/min	Tool Rotational speed rpm	Tool Shoulder Diameter 24	Tool shoulder diameter 18
40	1000		
	1200		
75	1000		
	1200		
105	1000		
	1200		

4.0 Conclusion

The following conclusions have drawn from the experimental study of the friction stir processing of AZ31 B magnesium alloy.

i. Defect free processed zone has been identified from the experimental work for the selected process parameters. Further the tool shoulder diameter has been identified as the critical parameter for creating the defect free processed zone.
ii. The process parameter for the defect free processed zone is observed when the tool shoulder diameter is 24 mm, tool traversing speed is 75 & 105 mm/min and the tool rotational speeds are 1000 & 1200 rpm respectively
iii. A fine equiaxed grain refinement is noticed in the nugget region with the average grain size of less than 10μm. Due to this the friction stir processed Az31B material can exhibit superplasticity characteristics.
iv. The percentage of elongation in the friction stir processed material increases from 1.2 to 1.82 times of the base material.

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